(NASA-CR-93396) TRANSISTOR FAILURE IN ENVIRONMENTAL CONTROL UNIT (Bellcomm, Inc.) 11 p
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BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Transistor Failure in Environmental Control Unit - Case 320

DATE: January 5, 1968

FROM: C. M. Klingman
C. H. Zierdt, Jr. (BTL)

## ABSTRACT

This memorandum documents the analysis of the 2N2891 transistor failure in the Environmental Control Unit (ECU) in the TV-2 spacecraft. The results of the first part of this analysis were presented to Dr. G. Low at Manned Spacecraft Center (MSC) on September 29, 1967. No conclusive evidence of the cause of failure has been established. One of the problems in trying to establish the cause of failure was the lack of historical test data on the individual 2N2891 failed transistor. The lack of historical test data was also one of the major problems in assessing the probability of the 2N2891 transistor performing satisfactorily in spacecraft 017.

As a result of the complete analysis, the following general comments can be made with respect to the circuit design:

1. The poor thermal environment of the 2N2891 transistor in the ECU module of the type used in spacecraft 017 increases the hazard of failure from either surface-degradation or electrical-overstress conditions.

2. System and component testing procedures should be carefully reviewed to reduce the hazard of damage to internal parts through excessive stress application.

It is the authors' understanding that present plans call for utilizing a 2N4300 transistor in future applications. The results of the analysis discussed in this report should be of value in evaluating the new design.

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MEMORANDUM FOR FILE

## INTRODUCTION

This memorandum documents the analysis of the Fairchild 2N2891 transistor failure in the Environmental Control Unit (ECU) in the TV-2 spacecraft. Dr. G. Low requested that Bellcomm perform this independent analysis and results were reported to him in an oral presentation at Manned Spacecraft Center (MSC) on September 29, 1967.* In response to Dr. Low's questions, it was stated that as a result of our analysis, we believed the 2N2891 transistor, if properly screened, was adequate for the circuit application in which it was being used, and that we could provide a specification for screening this device for this application.**

On September 29, Dr. Low asked Bellcomm to continue investigation into the cause of this failure to the extent of performing the tests on the clamping diode (a 1N418) which we identified as not having been completed as of that date. North American Rockwell and AiResearch have now completed these tests and an additional test of the transistor case temperature and the results are incorporated in this memorandum.

## ANALYSIS

The circuit configuration in which the 2N2891 transistor failed is shown in Figure 1. In performing the analysis of the 2N2891 failure the following data were considered: data available from life tests on this type of transistor chip; data taken on the circuitry, application, and environment; and system data recorded during the time of failure. All are discussed separately in the following paragraphs with associated conclusions based on each set of data. The assessment of the circuit used in Spacecraft 017 follows the discussions of this data.

*"Minutes of Meeting between Bellcomm, NASA, NAA and Boeing, September 29, 1967, to discuss 2N2891 transistor, Manned Spacecraft Center, Houston, Texas

**Such specification was delivered to MSC on October 6, 1967.

## Data on the Failed Transistor

The transistor had been mounted and cross-sectioned at Fairchild. A plane-view photograph showed a dark area on one end emitter stripe, not particularly significant of itself, but important because it was found to register exactly with a disturbed area in the silicon-aluminum interface on the transistor cross section taken at a right angle through this dark area. When viewing the cross section of this disturbed area, three significant spots were observed:

1. Two bubbles in the aluminum, with corresponding craters in the silicon, indicating substantial alloying.

2. A "pocket", in the silicon, displaying a burned appearance and apparently lined with burned aluminum.

3. A "pocket", in the silicon, apparently lined with a continuous coating of molten-solidified aluminum.

Electrical testing before sectioning showed 4.0 mA-40 V $C_{EO}$ and $C_{ES}$ leakage, high E-B leakage, and no transistor action at collector currents below 10-mA--typical of seriously-degraded E-B and C-B junctions.

Tests by Bell Telephone Laboratories have established that the 2N2891 transistor chip (in 2N2893 housing) withstands, with either a positive base drive or resistive E-B connection, current voltage levels in the "safe operating area" per Fairchild data sheets without second breakdown or other damage, in 15 samples tested. Although the failed device could have been a low-strength "freak" in this respect, excessive voltage-current from the circuit could also have caused the failure. A post-mortem examination of a device can not distinguish between these two causes.

Conclusion: Device was damaged by localized high current concentration--typical of second breakdown failure.

## Data From Life-Test Reports

Motorola Failure Analysis and Corrective Action Report No. 1040-3 (referring to Failure Analysis Reports 3014/515/1040-1 and -2) and AC Electronics TR-245-1 cited maximum-power life and/or screening tests in which significant numbers of Fairchild 2N2891 transistors had failed, primarily because of high collector emitter leakage current which was attributed to "channel" formation and/or surface leakage.

The majority of the failures reported were so classified at leakage currents of 50 or 100μA at 60 V $C_{EO}$; four devices of approximately 100 tested had leakage currents near the 4mA value which would constitute a failure in the ECU solenoid-switching application. No very-high-leakage failures were observed before 50 hours of life test at maximum-rated power.

Accelerated life testing of 2N2893 transistors by Bell Telephone Laboratories, Allentown, Pa. (in 1965 and 1966) showed:

1. No failures in 30 devices in 11,000 hours at TA=200°C, $V_{CB}$ = 10 Vdc, $V_{EB}$ = 3Vdc; a temperature acceleration of the "off" condition in the ECU application.

2. Some early "freak" failures in power-aging at average junction temperatures near 275° and 300°C, with relatively-long median life for the central population (tests continued to 4000-5000 hours). Significant failures were in high-leakage-current mode--magnitude of leakage current which constituted a failure was 100μADC.

Fairchild stated that the same transistor chip was used in 2N2891 and 2N2893 transistors, although they differed in external housings.

Conclusion: Some Fairchild 2N2893 devices fail in high-leakage-current mode, but remaining devices are relatively strong. The devices are not sensitive to simultaneous reverse-bias on both junctions at high temperature. None of the failures reported appeared to be of the nature of that seen in the ECU module (second-breakdown failure).

## Data from Circuit

Upon examination of the circuit, it appeared that any of the following circuit faults could have caused the observed type of transistor failure:

1. Open or Short-Circuited Clamp Diode Circuit

   An open diode circuit would allow the inductive "kick" from the solenoid coil, at turn-off, to be applied to the transistor. This kick would apply sufficient energy and voltage to cause reverse second breakdown. A shorted diode would apply $V_{cc}$

directly to the 2N2891 collector, with only power supply resistance limiting collector current; the resulting current was estimated to be sufficient to cause forward second breakdown.

The clamp diode associated with the failed transistor was removed from the failed module* by AiResearch personnel (after a considerable period of failure-free testing subsequent to replacement of the failed transistor) and examined by:

a. Microscope, after scraping off of paint coating. No evidence of short-circuiting (defective assembly or loose particle(s)) was seen; resin coating of junction area was visible.

**b. Monitored shock test: 3 blows each 1500 g-1/2ms, 3 directions @ $I_f$ = 1ma. No "open" indication.

**c. Temperature cycling test: -65°C to 200°C, 50 hours, 1 cycle/hour, $I_f$ = 1ma. No "open" recorded.

**d. Microscope, after dissecting diode. No evidence of arcing across intermittent open.

<u>Conclusion</u>: No evidence of clamp-diode-circuit failure.

2. <u>Partial Loss of Base-Drive to 2N2891</u>

Partial loss of base-drive could place the 2N2891 in a high-power-dissipating linear-operating mode, at a maximum power level near 2 watts under worst-case conditions. This condition could cause second-breakdown failure by thermal runaway if the device is not sufficiently cooled (see section below titled "Data from Environment").

<u>Conclusion</u>: From examination of the trigger-type base-driving circuit used, and the satisfactory operation of the solenoid circuit after replacement of the failed transistor, it is unlikely that the requisite intermediate-base-drive condition would occur during operation of the system.

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*Welded connections were examined and found to be sound.

**Tests performed by Autonetics subsequent to initial investigation 9/26 thru 29.

3. Slow Clamping

If the clamp circuit on the solenoid winding did not become effective very quickly, the inductive "kick" from circuit turn-off could damage the transistor by reverse second-breakdown. Measurements on eight simulated solenoid-transistor circuits and on the actual failed circuit (after replacement of the failed transistor) showed a maximum 3-volt $V_{CE}$ rise (above $V_{cc}$) during the clamping delay period. When the 2N2891 transistor was forced "off" more rapidly by negative base drive (to 0.2µ sec turn-off time, less than that of the fastest transistor observed by Fairchild in a production sample, under resistance-return base condition), a maximum 13-volt $V_{CE}$ rise (above $V_{cc}$) was observed. No measurable voltage "spike" occurred during clamp-circuit current decay. These voltages ($V_{cc}$ plus inductive "kicks" of 13 volts) would not represent a hazard to a normal 2N2891 transistor.

Conclusion: Slow clamping is not a likely cause for transistor failure in this circuit.

Data From Application

Application-related hazards would include application of excessive voltage (not sufficently current limited) to the base and collector by means of the terminals which are available at a wiring plug, or supplying insufficient base drive during testing of the module when disconnected from its system drive source. Personnel participating in testing of the failed module stated that wiring was not disturbed during the period of failure although a loss of vacuum did occur (see section below titled "System Data Taken During Time of Failure"), causing an interruption in system testing.

Conclusion: No firm evidence of a testing-procedure hazard was found. This possibility is difficult to trace unless the test is completely monitored and recorded.

Data from Environment

Environmental hazards would include temporary faults in associated circuitry and excessive temperature rise of the 2N2891.

The failed module had been vibrated while operating, without any indication of failure, prior to the failure observation.

Although the actual junction temperature had not been measured by North American Rockwell at the time of this investigation, it was reported that the potting surrounding the device had a thermal conductivity equivalent to that obtained by adding an approximately 0.5 in. dia. x 0.25 in. high clamp-on heat sink to the 2N2891; a rough calculation then yields thermal resistance near 0.11°c/mw. Hence at 100°C ambient, the device would not be expected to go into second-breakdown due to thermal runaway. However, the actual junction temperature would have to be measured to insure this fact.

North American Rockwell has subsequently measured the junction-temperature rise of the transistor as 15.3°C, after 1/2 hour of normal "on" operation at 125°C ambient. From an approximate $I_C$ = 180mA, and $V_{CE}$ (sat) = 0.1V for a saturated operating condition, this calculates to a thermal resistance of 0.85°C/mw, which is nearly 8 times that previously assumed. For this value of thermal resistance, dissipation of 410 mw should melt the junction area of a 2N2891 transistor, and 350 mw would represent extremely-hazardous operation. No data which indicated the probability of excessive transistor temperature rise were available.

Conclusions: The probability of a static-condition failure from temporary faults in associated circuitry, after no-failure during vibration, is quite small.

The probability of excessive temperature rise of the transistor could not be evaluated from the data at hand.

System Data Taken During Time of Failure

It was stated that failure of the test module occurred slowly, in that a digital voltmeter connected across the solenoid coil (which usually read near zero, with an upper allowable limit of 0.1 volt) was noted as showing a 0.2 volt reading after a period of ECS operation, and was noted as showing a high voltage reading (2 volts) after a cooling-system failure was observed; this voltage value indicated a solenoid current high enough to prevent closing of the solenoid-actuated water valve in response to the "turn-off" signal.

Such an increase in transistor leakage current could arise from 1) progressive degradation caused by repeated brief excursions into second breakdown, 2) thermal runaway caused by progressive heating during successive operating cycles, 3) surface degradation processes (accelerated by high temperatures and by voltage blocking in the off state), capable of causing thermal runaway if bad enough, or 4) overheating of the transistor during testing of the module, because of insufficient applied base drive. Among the most probable causes, the third hypothesis seems least probable, in view of the 2N2891 life-test data which show smaller degrees of degradation, occurring over longer periods of time, than would produce the type of transistor failure observed.

The evidence of gradual degradation of the collector cutoff current described above was to some extent compromised by data obtained during the ECU Design Review held at AiResearch on October 16 thru 18, 1967. At this review a strip-chart recording taken during TV-2 testing, which monitors the voltage across the solenoid in addition to other variables, was made available for the first time and was examined. From this record it can be established that the solenoid was operating properly just prior to a test interruption which was due to loss of vacuum. No indication of the duration of this interruption was available. Immediately upon resumption of the test, the recording shows improper solenoid behavior corresponding to a high leakage current through the 2N2891 transistor.

This evidence is suggestive of an externally-induced failure rather than a gradual degradation of the transistor, particularly since AiResearch advises that there have been a number of earlier cases of externally-induced failures of the 2N2891 transistor in this module.

Conclusion: We do not know exactly why the failed transistor apparently degraded slowly initially, and ended up in a semi-shorted condition which appears to be a result of second breakdown or other overstress-induced condition. In view of all the evidence available, it is considered highly probable that the overstress occurred during the testing of the module rather than during system operation. The probability of such damage is considerably increased by the relatively-poor cooling of the transistor as it is embedded in this module.

ASSESSMENT OF CIRCUIT USED IN SPACECRAFT 017

Unfortunately, the exact cause of the 2N2891 transistor failure in TV-2 was not determined from this analysis. Hence, it was impossible to predict with any degree of confidence whether the ECU in spacecraft 017 was prone to fail due to the same cause. However, the following comments could be made with respect to the circuit in spacecraft 017, prior to its successful performance:

1. On the basis of this analysis and a reading of $I_{CE_R}$ of the 2N2891 transistor in the spacecraft 017 circuit, there was some confidence that the device would not fail due to surface degradation effects.

2. Because the 2N2891 transistors were purchased as commercial parts from a distributor without any acceptance tests conducted prior to insertion into the ECU circuit, there was no way of knowing if the transistor in spacecraft 017 was representative of the normal population of such devices. Without such knowledge, estimation of individual component reliability is impossible.

As a result of our entire analysis, comments can be made with respect to the design, in general:

1. The relatively-poor thermal environment of the 2N2891 transistor in the ECU module increases the hazard of failure from either surface-degradation or electrical-overstress conditions. The fact that the thermal environment was grossly misjudged, and that the transistor-operating temperature had not been measured, is indicative of lack of attention to the thermal considerations which are known to be extremely critical in semiconductor-device applications. Thermal analysis should be routine.

2. System and component testing procedures should be carefully reviewed, to reduce the hazard of damage to internal parts through excessive stress application.

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1031-$^{CMK}_{CHZ}$-bjh

Attachment
Figure 1

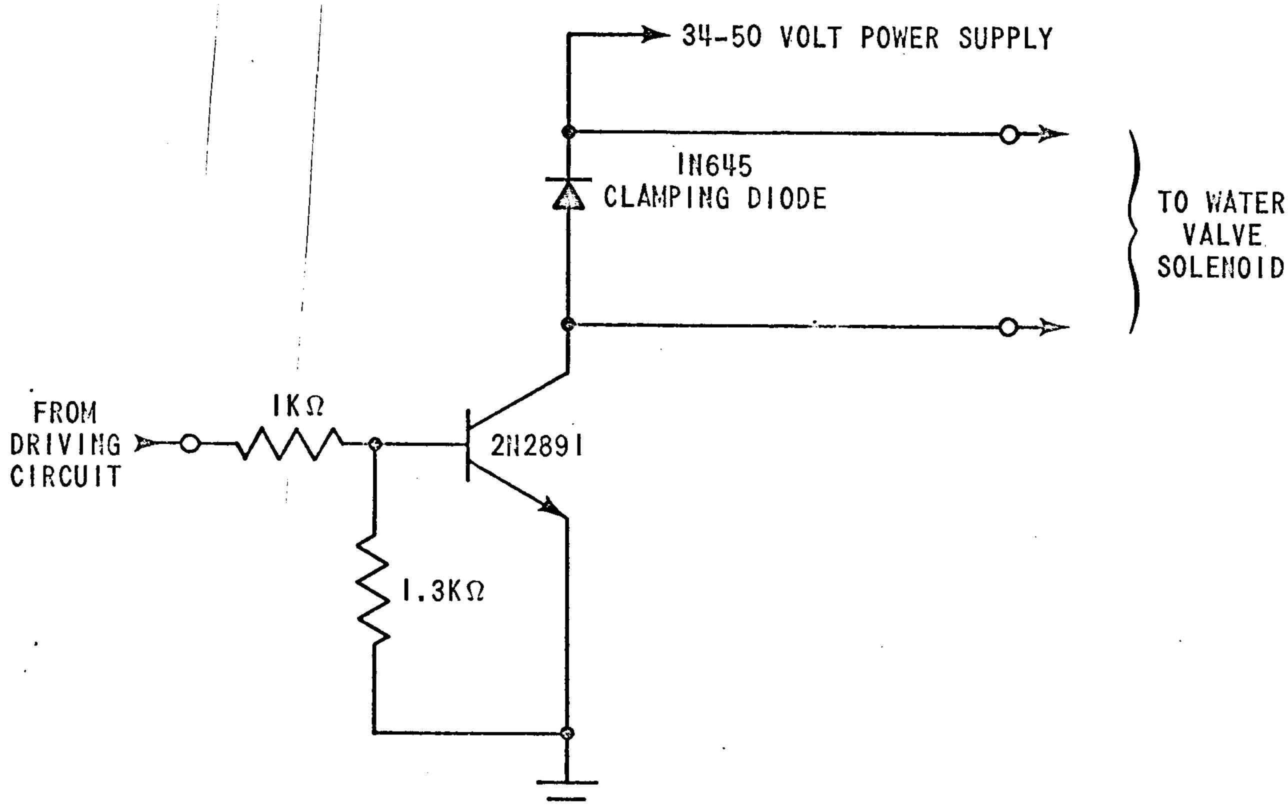


FIGURE I - CIRCUIT APPLICATION OF 2N2891 TRANSISTOR

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